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International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications: Summary of 5th Meeting

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September 2003

U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

TECHNOLOGY ADMINISTRATION
Phillip J. Bond, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Arden L. Bement, Jr., Director

Abstract

The 5th Meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications was hosted by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce and held at NIST headquarters at Gaithersburg, Maryland on May 2 and 3, 2002. The organizing Committee for the meeting included Moni Dey from the U.S. Nuclear Regulatory Commission (U.S. NRC), and Anthony Hamins from NIST. Thirty three participants from five countries attended the international meeting.

The purpose of the 5th meeting was mainly to discuss the results of Benchmark Exercise # 2, "Pool Fires in Large Halls," conducted in the project. Validation and regulatory applications of fire models were also presented and discussed in the meeting. The results presented for Part I of Benchmark Exercise # 2 were generally quite encouraging. While the general, qualitative, nature of the experiments had been captured in the simulations, a number of issues had arisen. Furthermore, the parametric analysis undertaken by a number of participants had yielded useful information. Different conclusions have been drawn on the most significant, or controlling, parameters. The combined effect of the choice of heat of combustion, combustion efficiency and radiative fraction was found to be an important factor. The validation and application of several, diverse fire models, ranging from empirical equations organized in worksheets to zone, lumped-parameter, and computational fluid dynamic (CFD) models, were presented and discussed at the meeting. The discussions emphasized the need to validate and determine the accuracy of such models, especially to understand the differences in the predictive capabilities and margins of uncertainty for the different types of models over a range of fire scenarios. This information is needed to establish safety factors and implement effective applications of these models in a regulatory framework. The need to define credible fire scenarios and generate data for fire sources, especially cable tray fires, was emphasized.

Table of Contents

Executive Summary

The 5th Meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications was hosted by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce and the U.S. Nuclear Regulatory Commission and held at NIST headquarters at Gaithersburg, Maryland on May 2 and 3, 2002. Thirty three participants from five countries, France, Germany, UK, Finland, and the US attended the international meeting.

The objective of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications is to share the knowledge and resources of various organizations to evaluate and improve the state of the art of fire models for use in nuclear power plant (NPP) fire safety analysis. The project is divided into two phases. The objective of the first phase is to evaluate the capabilities of current state-of-the-art fire models (empirical, zone, lumped-parameter, and CFD) for fire safety analysis in NPPs. The second phase will implement beneficial improvements to current fire models that are identified in the first phase, and extend the validation database of those models.

The 1st planning meeting of the project was held at the University of Maryland at College Park, USA, on October 25-26, 1999. The summary of the 1st meeting and the details of the objectives established for the project can be found in NUREG/CP-0170 (April 2000). The 2nd meeting of the collaborative project was hosted by the Institute for Protection and Nuclear Safety (IPSN), France and held at the IPSN offices at Fontenay-aux-Roses, France on June 19 and 20, 2000. The objective of the 2nd meeting was to discuss the definition of the 1st benchmark exercise in the project. The summary of the 2nd meeting can be found in NUREG/CP-0173 (July 2001). The 3rd meeting of the collaborative project was hosted by the Electric Power Research Institute (EPRI) and held at the EPRI offices in Palo Alto, California on January 14-15, 2001. The objective of the 3rd meeting was to discuss the results of the 1st benchmark exercise. Since the results of the 1st benchmark exercise were documented in NUREG-1758 (June 2002), formal proceedings of the 3rd meeting were not published. The 4th meeting of the collaborative projected was hosted by GRS, Germany and included discussions to finalize the report of the 1st benchmark exercise. A summary of the 4th meeting can be found in Report No. GRS-A-3106.

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30. Naeem Iqbal, NRC, USA
31. Mark Salley, NRC, USA
32. Chris Bajwa, NRC, USA
33. Sharon Steele, NRC, USA

The purpose of the 5th meeting was to discuss the preliminary results of the 1st part of the 2nd benchmark exercise in the project on pool fires in large halls. The specification of the 2nd part of the exercised was also discussed. Other topics discussed at the meeting included the regulatory application and validation of fire models. The full agenda of the 5th meeting is included in Appendix A.

<u>Results of Benchmark Exercise # 2, Part I, "Pool Fires in Large Halls</u>

The results presented for Part I were generally quite encouraging. While the general, qualitative, nature of the experiments had been captured in the simulations, a number of issues had arisen. Furthermore, the parametric analysis undertaken by a number of participants had yielded useful information. Different conclusions have been drawn on the most significant, or controlling, parameters, that impact the results presented in Part I.

For the purpose of calculating layer height and temperature, for which most of the measurement data had been collected, the zone model (CFAST) appeared to be fit for purpose. This was encouraging given the complexity introduced by the roof shape, for which an 'equivalent' flat ceiling sufficed. Analyses of the size and location of the 'infiltration' openings for case 1 and 2 indicated that the predictions were not sensitive to these parameters. This finding was supported by zone, lumped parameter, and CFD models.

While different models were in broad agreement, participants had not always agreed on the most sensitive parameters, i.e., what parameters were particularly critical in terms of their influence on the final predictions. An example here was the heat losses to the walls and ceiling.

The combined effect of the choice of heat of combustion, combustion efficiency and radiative fraction was found to be an important factor. It seems that the choice of 80% for the combined effect of combustion efficiency and radiative fraction was not ideal, resulting in too much heat being convected into the upper layer (and hence the predicted temperatures being higher than the measured ones). By selecting an appropriate balance of convective heat release rate (by modifying the combustion efficiency and/or radiative fraction) and heat losses to the boundaries, modelers could replicate the measured layer temperature quite closely.

Finally, there was a general trend to predict lower layer depths (i.e. closer to the floor) than those derived from the measurement data. This is perhaps a consequence of the post processing of the thermocouple data to derive smoke layer information.

Validation and Regulatory Applications of Fire Models

Papers were presented on the regulatory application of fire models by a user in a utility and staff of a regulatory agency and an industry research group. The papers identified the need for technology transfer from the research community to users, and education and training of both regulatory inspectors and plant staff. Increased dialogue between inspectors and plant staff and use of the same tools will lead to a common understanding of the models. There is a need for guidance on the use of models, and a good user interface for effective application of the models to prevent misuse. Worksheets based on empirical models available from handbooks were presented both by regulators and industry as a first systematic application of quantitative fire hazard analysis for nuclear power plants. These worksheets provide a means to transition from qualitative to quantitative inspection methods, and also serve as a design guide to support day-to-day operations. However, presenters and participants noted that although these empirical models provide a good start, they should not be treated as "gospel." It is necessary to establish the margins of uncertainty in these correlations by conducting validation exercises. These margins can then be used to establish safety factors in fire hazard analysis methods that will lead to acceptability of the analysis methods.

Participants also presented descriptions and validation results of a wide range of zone, lumped-parameter, and CFD models. Participants discussed and identified a need to transition from simple to more comprehensive and accurate tools. In order to identify the right tools for various regulatory applications, it is necessary to benchmark the different tools to develop their accuracy for a wide range of fire scenarios.

Participants discussed and noted that any type of fire model analysis requires establishing credible fire scenarios. Participants noted that current documents on the use of fire models in NPP applications have not addressed this item as yet. The absence of such information is a challenge in the current inspection process. Fire scenario definition should be identified as a priority in the research plan. Flame spread rate data in cable trays was also identified as a priority research item. The development of a comprehensive database of mass loss rate profiles for combustible materials in NPPs is essential for the efficient and broader application of fire models in fire safety analysis.

Foreword

The National Institute of Standards and Technology (NIST), U.S. Department of Commerce, in collaboration with the U.S. Nuclear Regulatory Commission, is pleased to publish the proceedings of the 5th meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications. Since the inception of the project in 1999, NIST and the U.S. NRC established an inter-agency memorandum of understanding and collaborated in conducting research to provide the necessary technical data and tools to support the use of fire models in nuclear power plant fire safety analysis. The joint sponsorship of the 5th meeting of the project and publication of these proceedings is a product of this collaboration. As is apparent from these proceedings, the international collaborative project is resulting in a significant exchange of useful technical information between participants in the project. NIST appreciates and values the technical information provided by all participants in this project. It would be difficult for a single organization to generate the diverse technical information collected through such a broad collaborative effort. NIST is pleased to be a partner and provide its contribution to the international collaboration through its participation in the project and publication of these proceedings.

James Hill, Deputy Director
Building and Fire Research Laboratory
National Institute of Standards and Technology
U.S. Department of Commerce

Acknowledgments

Support for administration and audio-visual arrangements for the meeting was provided by Wanda Duffin and Kevin McGrattan. Walter Jones and George Mulholland hosted the lunches for the participants at the NIST executive dining room.

Acronyms and Initialisms

BRE	Building Research Establishment
CIB	International Council for Research and Innovation in Building and Construction
CFAST	Consolidated Model for Fire and Smoke Transport
CFD	Computational Fluid Dynamics
COCOSYS	Containment Code System
EdF	Electricite de France
EPRI	Electric Power Research Institute
FDS	Fire Dynamics Simulator
GRS	Gesellschaft fuer Anlagen-und Reaktorsicherheit
HRR	Heat Release Rate
iBMB	Institut fuer Baustoffe, Massivbau und Brandschutz
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JASMINE	Analysis of Smoke Movement in Enclosures
NII	H. M. Nuclear Installations Inspectorate
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Analysis
VTT	Valtion Teknillinen Tutkimuskeskus
WPI	Worcester Polytechnic Institute

1 Introduction

The objective of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications is to share the knowledge and resources of various organizations to evaluate and improve the state of the art of fire models for use in nuclear power plant (NPP) fire safety analysis. The project is divided into two phases. The objective of the first phase is to evaluate the capabilities of current state-of-the-art fire models (empirical, zone, lumped-parameter, and CFD) for fire safety analysis in NPPs. The second phase will implement beneficial improvements to current fire models that are identified in the first phase, and extend the validation database of those models.

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The purpose of the 5th meeting was to discuss the preliminary results of the 1st part of the 2nd benchmark exercise in the project on pool fires in large halls. The specification of the 2nd part of the exercised was also discussed. Other topics discussed at the meeting included the regulatory application and validation of fire models. The full agenda of the 5th meeting is included in Appendix A.

2 Background

The first task of the collaborative project was to undertake a benchmark exercise to evaluate the current capability of fire models to analyze the hazard associated with cable tray fires of redundant safety systems in nuclear power plants. These systems are required to shutdown the reactor during an emergency, and when located inside the same compartment must be separated by a specified distance to ensure that a fire in one system does not cause the other to fail also. The exercise involved a series of hypothetical scenarios to predict cable damage inside an emergency switchgear room, and were fairly tightly specified in respect of the input and modeling parameters to be used. Due to the size of the room and the nature of the fire scenarios, the differences in the conclusions obtained using the various fire models were not significant. Target cable damage was predicted to be unlikely in almost all cases studied. A summary of the main results, findings and conclusions is included in NUREG-1758 (June 2002).

This section summarizes the second benchmark exercise. The main objectives taken into consideration when selecting the second benchmark exercise were:

- To examine scenario(s) that provide a harder test for zone models, in particular with respect to fire spread in large volumes representative of, say, a turbine hall.
- If possible, to make use of experimental data to fulfil the requirement of more thoroughly testing the predictive capability of both zone and CFD fire models. Again, the emphasis when selecting scenarios was on large smoke filling volumes.

Benchmark Exercise # 2 is divided into two parts. For the first part there are experimental measurements of temperature and velocity against which model predictions can be compared. The second part extends the scope of the exercise to examine the consequence of larger fires, but for which there are no experimental measurements against which to compare.

Part I includes three cases, based on a series of full-scale experiments inside a test hall with dimensions 19 m high by 27 m long by 14 m wide (i.e., floor area 378 m^2). Each case involves a single fire (2 MW to 4 MW), and for which there are experimental measurements of gas temperature and doorway velocity. The height of a turbine hall within an NPP (c. 25 m) is similar to that of the test hall although it is acknowledged that the area of a turbine hall (c. 3500 m^2) is much greater. However, the test hall is one of the largest enclosures for which fire test data is available for comparison with model predictions. The preliminary results of Part I were presented and discussed at the 5th meeting.

Part II includes three additional cases for which experimental measurements do not exist, but extend the scope of the benchmark exercise to examine the effect of a bigger fire and larger floor area representative of a hydrocarbon pool fire in a real turbine hall. These are optional cases for participants to investigate if time and resources allow. The specification of Part II was discussed at the 5th meeting.

Although most input parameters are defined, Benchmark Exercise # 2 does in a few respects involve a greater degree of user judgement in setting up the problem compared to the first benchmark exercise. This applies in particular to the treatment of the sloping roof (with zone models) in Part I. Appendix B includes the full specification document for Benchmark Exercise # 2.

3 Meeting Summary

The following provides a summary of the main topics discussed at the meeting, the 2^{nd} benchmark exercise, and the validation and regulatory application of fire models. Summary papers submitted for the proceedings and slides used by the presenters are included in Appendices C and D, respectively.

3.1 Benchmark Exercise # 2, "Pool Fires in Large Halls"

Summary

Session IV was devoted to the second benchmark exercise (Fire in a Large Hall). This has been selected to challenge fire models in respect to issues not addressed in the first exercise, e.g., the effects of fire in a large volume representative of, say, a turbine hall. Furthermore, it includes some scenarios for which there are experimental measurements, allowing comparisons to be undertaken.

Benchmark Exercise # 2 is divided into two parts. For the first part there are experimental measurements of temperature against which model predictions can be compared. The second part extends the scope of the exercise to examine the consequence of larger fires, but for which there are no experimental measurements to compare against.

The session was devoted mainly to presentations and discussions on simulations of Part I, where various participants had made comparisons between predicted and measured data. This was followed by a discussion of the format for Part II of the benchmark exercise, so that the problem definition could be finalized before participants undertook simulations.

Benchmark Exercise # 2 - Part I

S. Miles introduced Part I at the start of the session. It includes three cases, based on a series of full-scale experiments inside a test hall with dimensions 19 m high by 27 m long by 14 m wide. Each case involves a single fire, in the range 2 MW to 4 MW, and for which there are experimental measurements of gas temperatures at various locations inside the hall, in particular at the location of three vertical thermocouple trees.

The problem specification included in Appendix B contains full details of the tests, and the requirements for the numerical simulations. It was released in conjunction with a summary of the measurement data against which to compare predictions, and so Part I is therefore an informed study rather than a blind simulation exercise. Nevertheless, participants have been invited to make quantitative comparisons between predictions and measurements, and to draw conclusions where possible.

Six presentations were made at the meeting, covering ten sets of predictions, including three examples of CFAST, two of FDS, two of JASMINE and one each of COCOSYS, HADCRT and CFX.

Presentations

Jonathan Barnett - Class Exercise using CFAST, JASMINE and FDS

The presentation was made by J Barnett on behalf of nine students studying performance-based fire design as part of an undergraduate course at Worcester Polytechnic Institute. Most students had some experience in the fire protection industry. However, prior to the exercise they had only had limited experience of zone models, and none had any CFD experience.

The students had been divided into three groups, one group using FDS, one group using JASMINE (via the JOSEFINE user interface) and one group using CFAST. The presentation focussed more on general observations rather than detailed comparisons. With all three models the students had found the sloping roof a challenge. For the zone model (CFAST) an equivalent flat ceiling had been specified. For both CFD models they had found setting up the sloping roof to be time consuming. Probably the biggest 'complaint' of the CFD models was the long simulation times compared to zone models, making sensitivity analysis difficult. Another issue was in calculating layer heights and temperatures from CFD data.

Two options had been investigated for setting the height of the equivalent flat ceiling in CFAST; conserving the enclosure volume and conserving the enclosure surface area. However, it was found that the choice had no significant effect on the results. The students had been unsuccessful in specifying mechanical exhaust ventilation for case 3.

Predictions for gas temperature were considered to appear reasonable for all models. Given that they had used the models with little, or no, prior fire modelling experience and were left in the main unsupervised, the outcome of the exercise was quite promising. However, the students had found the models quite difficult to use, and stressed the need for good guidance on their use.

Walter Klein-Hessling - COCOSYS (lumped parameter) and CFX-4 (CFD)

W Klein-Hessling presented work that he had undertaken with the lumped parameter model COCOSYS and that his colleague, W Heitsch, had performed with the CFD model CFX-4. Most work had been undertaken with COCOSYS at this stage.

COCOSYS had been set up with approximately 500 (lumped parameter) control volumes, with individual ones located the thermocouple locations so that a detailed comparison against those measurements could be made. The COCOSYS simulations had taken about three hours for each case.

Reasonable agreement between predicted and measured temperatures at the three thermocouple trees had been achieved with COCOSYS once the combustion efficiency had been reduced by a further 40 %. In the specification document a plume radiative fraction of 20 % had been suggested, which had been equated to a reduced combustion efficiency. Another useful finding from the COCOSYS study was that varying the location of the infiltration openings for case 1 and 2 had little effect on the results. Heat loss to the walls and ceiling had been varied, but while this modified the gas temperatures by up to 20 °C, this was less than the effect produced by reducing the combustion efficiency.

COCOSYS had under predicted the plume temperature, which is a consequence of there being no plume model and the control volumes above the fire being relatively large (compared to those typically used in CFD). Furthermore, the spread in temperatures at the thermocouple column locations was greater in the COCOSYS results than in the measurements, which may be a consequence of not solving for momentum conservation. It was suggested that the COCOSYS pyrolysis model could have been used, which predicts the mass release rate of fuel. However, additional information about the fire source would have been required.

Only preliminary simulations had been performed with CFX. However, the temperature predictions were currently too high. Furthermore, numerical stability problems had been encountered, especially with case 3 (with mechanical ventilation). The problem of generating layer interface and temperature information from a CFD simulation was raised. The CFX simulations had taken about one week each.

A general remark was made that the use of a fixed convective heat transfer coefficient (10 J s-1 m-2 K-1) was too simplistic.

Amber Martin - CFAST (zone)

This presentation was from a practicing consultant's perspective. CFAST version 3.1.6 had been used to simulate Part I. As the presenter had not received the experimental summary data, the simulations had been performed blind. It was encouraging to see that the CFAST predictions for layer height and temperature were in line with those produced by the other participants. Upper layer temperatures were quite close to the measurements, and the predicted layer height descended to a lower value than that indicated by the measurement data. As for the other CFAST participants, an equivalent flat ceiling had been modeled (conserving enclosure volume).

Boro Malinovic - HADCRT (lumped parameter)

This presentation covered the second of the lumped parameter models. HADCRT was developed initially for explosions and other accidents, but is being extended to include fire modelling. In contrast to the COCOSYS simulations, relatively few 'junctions' were employed and so the modelling was more akin to that of a zone model. Consequently, simulations took only a few minutes.

The upper layer temperature predictions were quite close to the experimental values but the layer was predicted to descend closer to the floor. Although radiation had been ignored in the simulations reported, about (20 to 25) % of the heat was transferred to the boundaries (by convection).

It was suggested that a parametric analysis of the effect of varying the size and location of the infiltration openings for case 1 and 2 be performed, as this may be important. In particular, it may influence the lower layer temperature.

Kevin McGrattan - FDS (CFD)

The FDS simulations were undertaken as specified, except that 35% of the heat release rate was assigned to plume radiation (instead of 20 %). FDS version 2 was used, with five mesh blocks (one at the plume with a mesh resolution of 10 cm and four in the rest of the hall with a resolution of 40 cm). A total of approximately 200,000 grid cells were used in the simulations. Using this grid, good agreement between predicted and measured temperatures at the three thermocouple columns was demonstrated.

There was some discrepancy in the plume temperatures, particularly at the lower thermocouple location (about 100°C discrepancy for case 1). This was attributed to limitations of the combustion model, and it was suggested also that if the plume had leaned slightly in the experiments then this feature would most likely be missed in the simulation, which would still 'pick up' the hot temperature on the plume centre-line. Better plume temperature agreement was achieved in case 2 and 3 (with the larger fire size), which was attributed to there being more grid cells across the width of the plume compared to case 1.

Earlier simulations had been undertaken with a single mesh block, resulting in a coarser grid at the plume. The temperature agreement was not as good with this grid, with the predicted values being too high. This was attributed to the grid size being too great, with the result that the air entrainment was under-predicted and thus the ceiling layer was then too hot. It was stressed that grid size in the plume was critical in the LES approach, and that six to eight grid cells across the diameter of the fire source were required. This led onto a discussion on how engineers should be guided on this, and also on related numerical and modeling issues.

Stewart Miles - JASMINE (CFD) and CFAST (zone)

This presentation covered simulations using JASMINE and CFAST (used in conjunction with the FAST graphical interface). A sensitivity analysis had been performed with CFAST on a number of parameters, in particular the heat losses to the boundaries and the size and location of the infiltration openings for case 1 and 2. A more limited sensitivity analysis had been undertaken with JASMINE, examining again the boundary heat losses and the infiltration openings. A grid sensitivity analysis had been performed with JASMINE.

In common with the approach adopted by other participants, CFAST was run with a flat ceiling with a height set to conserve the volume of the enclosure for most simulations. Sensitivity to ceiling height had been investigated. 'Baseline' CFAST simulations were performed using the specified combination of sheet metal and mineral wool. However, to investigate the sensitivity to boundary heat loss, simulations had been performed with metal only, mineral wool only and non-conducting (adiabatic) surfaces. For case 1 and 2 the sensitivity to the size and location of the 'infiltration' openings had been investigated. Here the original 0.5 m^2 openings were replaced first by 0.01 m^2 openings and then by two large (16 m^2) openings. The effect of increasing/decreasing the height of the openings (above the floor) had been studied too.

The CFD (JASMINE) simulations had been performed using a numerical mesh of approximately 130,000 elements. A mesh resolution sensitivity study, using a mesh with eight times the number of elements, was reported. Heat losses to the boundaries had been modeled using a thermal penetration model, assuming only the mineral wool material. The effect of increasing the boundary heat losses (by modifying the thermal properties of the material) had been investigated.

The presentation reported that probably the most important finding, demonstrated by both the zone and CFD models, was the sensitivity of the gas temperatures to the conduction losses at the walls and ceiling. In the CFAST simulations the closest agreement with measurement was obtained by using either a sheet metal and mineral wool two-layer combination or by using the sheet metal alone. In the JASMINE simulations closer agreement with measurement was obtained when the conduction losses were increased. It was suggested that the conduction into the steel might be important. The smoke layer height, however, seemed to be less sensitive to the boundary conduction loss calculation.

The CFAST study indicated that while the upper layer temperature is sensitive to the choice of ceiling height, the layer height is sensitive only during the initial stage of the fire. Both the zone model and CFD simulations had indicated that the exact choice of 'infiltration' openings in cases 1 and 2 was not critical.

Reasonable agreement has been shown between measured plume temperatures and those predicted in the JASMINE simulations. The mesh refinement study had indicated some sensitivity to this parameter, with the finer mesh producing results closer to those measured.

Summarizing Remarks

The results presented for Part I were generally quite encouraging. While the general, qualitative, nature of the experiments had been captured in the simulations, a number of issues had arisen. Furthermore, the parametric analysis undertaken by a number of participants had yielded useful information. Different conclusions have been drawn on the most significant, or controlling, parameters.

For the purpose of calculating layer height and temperature, for which most of the measurement data had been collected, the zone model (CFAST) appeared to be fit for purpose. This was encouraging given the complexity introduced by the roof shape, for which an 'equivalent' flat ceiling sufficed. Analyses of the size and location of the 'infiltration' openings for case 1 and 2 indicated that the predictions were not sensitive to these parameters. This finding was supported by zone, lumped parameter and CFD models.

While different models were in broad agreement, participants had not always agreed on the most sensitive parameters, i.e. what parameters were particularly critical in terms of their influence on the final predictions. An example here was the heat losses to the walls and ceiling.

The combined effect of the choice of heat of combustion, combustion efficiency and radiative fraction was found to be an important factor. It seems that the choice of 80 % for the combined effect of combustion efficiency and radiative fraction was not ideal, resulting in too much heat being convected into the upper layer (and hence the predicted temperatures being higher than the measured ones). By selecting an appropriate balance of convective heat release rate (by modifying the combustion efficiency and/or radiative fraction) and heat losses to the boundaries, modelers could replicate the measured layer temperature quite closely.

Finally, there was a general trend to predict lower layer depths (i.e. closer to the floor) than those derived from the measurement data. This is perhaps a consequence of the post processing of the thermocouple data to derive smoke layer information.

Benchmark Exercise # 2 - Part II

Part II is a 'hypothetical' example for which there are no experimental measurements. However, the dimensions of the building are greater than in Part I, and have been selected to more closely represent a turbine hall.

The current specification for Part II (as at the time of the meeting) was summarized by S Miles. The fire source was representative of a large hydrocarbon pool fire. 'Target' cables and beams had been included, for which the likelihood of thermal damage was to be estimated. Although the building geometry was rectangular, in some of scenario cases there was the added complexity of an internal ceiling, effectively dividing the space into two connected compartments. There then followed a general discussion on what, if any, modifications should be made before participants proceeded to model the cases.

Modelers seemed keen to undertake simulations of Part II. However, while some participants wished for a bigger fire (> 200 MW), others wanted a smaller one. It was decided to keep the fire size as it was currently specified (i.e. growing to about 70 MW). The other main changes that were agreed or suggested were:To reduce the number of cases to be modelled to three.

- To include the internal ceiling, dividing the hall into a lower and upper deck, in all cases.
- To introduce a second opening in the internal ceiling.
- To increase the mechanical extraction rate to 24 m^3/s and 120 m^3/s for the cases where this is included.

There was an interest in the ability of models to predict the flow distribution through the hatch opening(s), which might be quite complex. It was agreed to add the calculation of net up/down mass and heat fluxes through the opening(s) to the list of predicated variables.

Note that following the meeting the specification for Part II was revised and presented on the web pages of the collaborative project for comment. The final specification was made available to participants on 5th June 2002.

3.2 Validation and Regulatory Applications of Fire Models

Three papers were presented on the regulatory application of fire models by a user in a utility, and staff in a regulatory agency and industry research group. The papers identified the need for technology transfer from the research community to users, and education and training of both regulatory inspectors and plant staff. Increased dialogue between inspectors and plant staff and use of the same tools will lead to a common understanding of the models. There is a need for guidance on the use of models, and a good user interface for effective application of the models to prevent misuse. Worksheets based on empirical models available from handbooks were presented both by regulators and industry as a 1st systematic application of quantitative fire hazard analysis for nuclear power plants. These worksheets provide a means to transition from qualitative to quantitative inspection methods, and also serve as a design guide to support day-to-day operations. However, presenters and participants noted that although these empirical models provide a good start, they should not be treated as "gospel." It is necessary to establish the margins of uncertainty in these correlations by conducting validation exercises. These margins can then be used to establish safety factors in fire hazard analysis methods that will lead to acceptability of the analysis methods.

Participants also presented descriptions and validation results of a wide range of zone, lumped-parameter, and CFD models. Participants discussed and identified a need to transition from simple to more comprehensive and accurate tools. In order to identify the right tools for various regulatory applications, it is necessary to benchmark the different tools to develop their accuracy for a wide range of fire scenarios.

Participants discussed and noted that any type of fire model analysis requires establishing credible fire scenarios. Participants noted that current documents on the use of fire models in NPP applications have not addressed this item as yet. The absence of such information is a challenge in the current inspection process. Fire scenario definition should be identified as a priority in the research plan. Flame spread rate data in cable trays was also identified as a priority research item. The development of a comprehensive database of mass loss rate profiles for combustible materials in NPPs is essential for the efficient and broader application of fire models in fire safety analysis.

3.3 Future Tasks and Benchmark Exercises

Session V of the meeting included presentations and discussion of proposed benchmark exercises for the project. Participants agreed to proceed with planning of these proposed exercises (which are summarized below) at the 6th project meeting scheduled for October 2002.

I. Benchmark Exercise # 3, "Cable Targets in Single Compartment Fires": This benchmark exercise will entail blind simulation of tests in a full-scale single compartment that will be sponsored by NRC and conducted at NIST. The size of the compartment will be representative of those in NPPs, and the fire source will be moderate sized hydrocarbon fires. The goal of these tests is to confirm the findings of Benchmark Exercise # 1 and focus on the issues that arose from that exercise, namely, the prediction of heat flux incident on target cable trays and the thermal response of the target.

II. Benchmark Exercise # 4, "Large Kerosene Pool Fires": This benchmark exercise will entail blind simulation of large kerosene pool fires in a single compartment. The tests will be sponsored by GRS and conducted at iBMB. The goal of the tests is to develop basic data for simulating kerosene fires under different boundary conditions, and to examine the ability to calculate the fire effects for selected scenarios. The benchmark exercise will focus on one of the test scenarios in the program.

III. Benchmark Exercise # 5, "Flame Spread in Cable Tray Fires": This benchmark exercise will entail simulation of cable tray fires and their effects in a single compartment. The tests will be sponsored by GRS and conducted at iBMB. Vertical and horizontal cable trays, different types of cables, and degree of cable preheating will be examined in the test program. The benchmark exercise will focus on one of the test scenarios in the program.

IV. Benchmark Exercise # 6, Target Heating in Divided Compartments: This benchmark exercise will entail the blind simulation of tests in the compartment used in Benchmark Exercise # 3, but divided with half walls to be more representative of NPP compartments. The exercise will focus on the effects of the half walls on flow and radiation shielding within the compartment. These tests will be sponsored by NRC and conducted at NIST.

V. Benchmark Exercise # 7: This benchmark exercise will be conducted in the compartment used for Benchmark Exercises #s 3 and 6 and focus on examining issues that are identified in those exercises and require further examination. These tests will be sponsored by NRC and conducted at NIST.

Appendix A: Agenda for Meeting

Agenda

5th Meeting of the International Collaborative Fire Model Project

Co-sponsored by the U.S. Nuclear Regulatory Commission, and the National Institute of Standards and Technology, U.S. Department of Commerce

May 2-3, 2002
National Institute of Standards and Technology,
Gaithersburg, Maryland, USA

Meeting Co-chairs: **Moni Dey, U.S. NRC and Anthony Hamins, NIST, USA**

Meeting Location: Lecture Room E, Administration Building (101), NIST, Gaithersburg, Maryland

May 2, 2002

8:30-9:50 AM ***Session I: Opening Remarks and Research Programs***

Session Chair: Anthony Hamins, NIST, USA

Introductions: **Workshop Participants**

Opening Remarks and Research Programs

1. "U.S. NRC Goals and Plans for Research to Support Risk-Informed Regulation," **Mark Cunningham**, Chief, Probabilistic Risk Assessment Branch, Office of Nuclear Regulatory Research, U.S. NRC

2. "Mission and Programs at NIST for Building and Fire Research," **James Hill**, Deputy Director, Building and Fire Research Laboratory (BFRL), NIST, USA

3. "Summary of Ongoing Projects at the Fire Research Division at BFRL, NIST," **Anthony Hamins**, Leader, Analysis and Prediction Group, BFRL, NIST, USA

4. "Future Fire Research at IPSN: Selection and Identification of Fire Scenarios and Research Needs," **Remy Bertrand**, IPSN, France

9:50-10:10 AM ***Coffee Break***

10:10-11:40 AM ***Session II: Regulatory Applications of Fire Models***

Discussion Leader: Moni Dey, U.S. NRC

1. "First Applications of a Quantitative Fire Hazard Analysis Tool for Inspection in U.S. Commercial Nuclear Power Plants," **Naeem Iqbal** and **Mark Salley**, U.S. NRC

2. "Risk-Informed Applications of Fire Models," **Doug Brandes**, Duke Power Company, USA

3. "EPRI Fire Modeling Project: A Guide for Nuclear Power Plant Applications," **Bob Kassawara, Bijan Najafi**, and **Francisco Joglar-Billoch**, EPRI, USA

11:40 AM - 1:00 PM *Lunch*

1:00 - 4:45 PM *Session III: Validation of Fire Models*

Discussion Leader: Anthony Hamins, NIST, USA

1. "Summary of Validation Studies for the FLAMME_S Code," **Chantal Casselman**, IPSN, France

2. " Zone Model Validation for Room Fire Scenarios," **Olavi Keski-Rahkonen & Simo Hostikka**, VTT, Finland

3. "The Zone Fire Model, MAGIC : A Validation and Verification Principle," **Bernard Gautier,** EdF, France

4. "Enhancements to the FIVE Methodology, **Fred Mowrer**, UMD, USA

Break

5. "Zone Modeling Theory, Applications and Certainty - the Verification and Validation of CFAST," **Walter Jones**, NIST, USA

6. "CFD Simulation of a 3.5 MW Oil Pool Fire in a Nuclear Power Plant Containment Building Using Multi-block Large Eddy Simulation," **Jason Floyd**, NIST, USA

7. "Verification, Validation, and Selected Applications of the VULCAN and FUEGO Fire Field Models," **Louis Gritzo**, SNL, USA

4:45-5:30 PM "NIST Large Fire Facility," George Mulholland, NIST, USA
Presentation and tour of test facility.

7:30 PM *No Host Dinner - Joe's Crab Shack, Kentlands, Gaithersburg*

May 3, 2002

8:30 AM - 12:00 Noon *Session IV: Preliminary Results of Benchmark Exercise # 2, Part I, Evaluation of Fire Models for Nuclear Facility*

Applications: Pool Fires in Large Halls

Discussion Leader: Stewart Miles, BRE, UK

1. "Specification of Benchmark Exercise # 2, Part I," **Stewart Miles**, BRE, UK

Preliminary Results

	Presenter	*Code Exercised*
2.	**Walter Klein-Hessling**, GRS, Germany	COCOSYS (lumped parameter)
3.	**Mathias Heitsch**, GRS, Germany	CFX (CFD)
4.	**Jonathan Barnett**, WPI, USA	WPI Class Exercise
5.	**Amber Martin and Alan Coutts**, Westinghouse, USA	CFAST (zone model)
6.	**Boro Malinovic**, Fauske Associates, USA	HADCRT (lumped parameter)

12:00-1:00 PM *Lunch*

1:00-2:30 PM *Session IV Continued: Benchmark Exercise # 2*

Discussion Leader: Stewart Miles, BRE, UK

7.	**Kevin McGrattan**, NIST, USA	FDS (CFD)
8.	**Stewart Miles**, BRE, UK	JASMINE (CFD), CFAST

9. "Proposal for Part II of Benchmark Exercise # 2, **Stewart Miles**, BRE, UK
10. Comments on Proposal for Part II of Benchmark Exercise # 2, **Workshop Participants**

2:30-2:45 PM *Break*

2:45-4:00 PM *Session V: Future Tasks and Benchmark Exercises*

Discussion Leader: Moni Dey, U.S. NRC

1. "Detector Response Modeling," **Doug Beller**, NFPA, USA
2. "A New Model for the Time Lag of Smoke Detectors," **Olavi Keski-Rahkonen**, VTT, Finland
3. "Proposed Benchmark Exercise for Cable Fire Tests in NPP-Type Compartments," **Marina Rowekamp**, GRS, Germany
4. "Proposed Benchmark Exercise for Kerosene Pool Fire Tests in Containment Building," **Marina Rowekamp**, GRS, Germany
5. "Challenges in use of State-of-the-Art Fire Modeling Tools in Nuclear Power Plant Applications," **Bob Kassawara, Bijan Najafi**, and **Francisco Joglar-Billoch,** EPRI,

USA

6. "NRC Plans for Fire Tests for Model Benchmark Exercises," **Moni Dey**, U.S. NRC

4:00-5:00 PM ***Session VI: Task Scheduling and Project Management***

Discussion Leader: Moni Dey, U.S. NRC

5:00 PM ***Workshop Concludes***

5:00-5:30 PM ***Optional Tour of NIST Fire Detector Laboratory***

All papers are allotted 20 minutes for presentation and 5 minutes for discussion.

Appendix B: Specification of Benchmark Exercise # 2

International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications

Specification for *Benchmark Exercise # 2*

Fire in a Large Hall

Issue 1 - February 2002

Introduction

In October 1999 the U.S. Nuclear Regulatory Commission and the Society of Fire Protection Engineers organised a planning meeting of international experts and practitioners of fire models to discuss the evaluation of numerical fire models for nuclear power plant applications [1]. Following this meeting an international collaborative project was set up with a view to sharing knowledge and resources from various organisations and to evaluate and improve the state of the fire modelling methods and tools for use in nuclear power plant fire safety.

The first task of the collaborative project was to undertake a benchmark exercise to evaluate the current capability of fire models to analyse the hazard associated with cable tray fires of redundant safety systems in nuclear power plants. These systems are required to shutdown the reactor during an emergency, and when located inside the same compartment must be separated by a specified distance to ensure that a fire in one system does not cause the other to fail also. The exercise involved a series of hypothetical scenarios to predict cable damage inside an emergency switchgear room, and were fairly tightly specified in respect of the input and modelling parameters to be used. Results and analyses were presented at a meeting at EPRI, California, in January 2001. Due to the size of the room and the nature of the fire scenarios, the differences in the conclusions obtained using the various fire models were not significant. Target cable damage was predicted to be unlikely in almost all cases studied.

This document defines the second benchmark exercise. It has been selected to challenge fire models in respect to issues not addressed in the first exercise, e.g. effects of fire in a large volume representative of, say, a turbine hall. Furthermore, it includes some scenarios for which there are unpublished experimental measurements, allowing comparisons to be undertaken.

Objectives of *Benchmark Exercise # 2*

Benchmark Exercise # 1 [2] focussed on an evaluation of fire models for predicting cable damage in an emergency switchgear room. A summary of the main results, findings and conclusions is included in the Technical Reference Report [3].

The main objectives taken into consideration when selecting the second benchmark exercise were:

1. To examine scenario(s) that provide a harder test for zone models, in particular with respect to fire spread in large volumes representative of, say, a turbine hall.

2. If possible, to make use of experimental data to fulfil the requirement of more thoroughly testing the predictive capability of both zone and CFD fire models. Again, the emphasis when selecting scenarios was on large smoke filling volumes.

Summary of Selected Scenarios

Benchmark Exercise # 2 is divided into two parts. For the first part there are experimental measurements of temperature and velocity against which model predictions can be compared. The second part extends the scope of the exercise to examine the consequence of larger fires, but for which there are no experimental measurements against which to compare.

Part I includes three cases, based on a series of full-scale experiments inside a test hall with dimensions *19 m* high by *27 m* long by *14 m* wide (i.e. floor area *378 m^2*). Each case involves a single fire (2 - 4 *MW*), and for which there are experimental measurements of gas temperature and doorway velocity. The height of a turbine hall within an NPP (c. *25 m*) is similar to that of the test hall although it is acknowledged that the area of a turbine hall (c. *3500 m^2*) is much greater. However, the test hall is one of the largest enclosures for which fire test data is available for comparison with model predictions.

Part II includes three additional cases for which experimental measurements do not exist, but extend the scope of the benchmark exercise to examine the effect of a bigger fire and larger floor area representative of a hydrocarbon pool fire in a real turbine hall. These are optional cases for participants to investigate if time and resources allow.

Although most input parameters are defined, *Benchmark Exercise # 2* does in a few respects involve a greater degree of user judgement in setting up the problem compared to the first benchmark exercise. This applies in particular to the treatment of the sloping roof (with zone models) in Part I.

Scheduled Activities

1. <u>February 2002</u>

   Release final version of the problem definition for *Benchmark Exercise # 2*, to be made available from the collaborative project document library, together with a summary of the experimental measurement data analysis for the Part I cases. The released data for Part I will include temperatures at three thermocouple tree locations, velocities in the open doorways (case where they are open) and calculated layer height and upper layer temperature (derived from the thermocouple measurements and a two-zone assumption).

2. <u>February to September 2002</u>

   Participants to perform simulations of Part I, and if time and resource allows, Part II.

3. <u>2nd/3rd May 2002 (5th project meeting at NIST)</u>

   Participants invited to present any preliminary numerical predictions and analysis for Part I at the 5th project meeting at NIST, USA. This will provide an opportunity for those participants who have started work on Part I of the benchmark exercise to discuss their initial results and findings.

4. <u>6th September 2002</u>

   Participants to send to BRE their 'final' numerical predictions for Parts I and II (if undertaken) in either a text file or Excel spreadsheet. Participants should also provide a brief summary of the modelling assumptions used for each case reported. Guidelines on the information required are given in the case descriptions below.

5. <u>October 2002 (6th project meeting at BRE)</u>

   BRE to present an overview of the results based on the information supplied.

   Participants to present their results and findings for Parts I and II (if undertaken). This will follow a similar format to that adopted for the first benchmark exercise at the 3rd project meeting at EPRI, USA.

6. <u>December 2002.</u>

   Draft technical reference document on the second benchmark exercise released. To be compiled by BRE and including technical annexes from the other participants as for the first technical reference document.

Part I – Large Hall Tests

Introduction

The three cases defined here are based on a series of full-scale fire tests inside a large hall. In each case a pool of heptane burned for approximately five minutes, during which time gas temperatures were measured at three thermocouple columns and at two thermocouple locations directly above the fire source. In two cases the hall was nominally closed, while for the third case a mechanical extract system was operational and two 'doorway' openings were provided.

For each case, two tests were performed under nominally identical conditions. Performing a repeat test allowed the variation in measured values due to changing ambient conditions (and other factors) to be investigated. In all three cases the repeatability of the measurements was reasonably good. The mass release rate of fuel for each of the three cases given below is the average from the two tests for that case.

Geometry

Figure 1 shows the geometry of the hall, comprising a rectangular space with a pitched roof structure above. A Cartesian axis system is defined, with the origin as indicated. All dimensions are in metres. The four walls are labelled as *west* (*x=0*), *east* (*x=27 m*), *south* (*y=0*) and *north* (*y=13.8 m*). Here the *west* and *east* walls known collectively as the end walls and the *south* and *north* walls as the side walls.

In cases 1 and 2 there are two open doorways, *0.8 m* wide by *4 m* high, one located in each end wall. Both doorways open to the external ambient environment, and are located such that the centre is *9.3 m* from the *south* wall (*y=9.3 m*). The doorway openings are labelled as the *west* doorway (door 1) and the *east* doorway (door 2).

Figure 2 shows the internal geometry of the test hall for Part I, including the location of the fire source.

A single mechanical exhaust duct is located in the roof space, running along the centre *y*-plane. It has a circular section with a diameter *1 m*, and opens horizontally to the hall at a distance *12 m* from the floor and *10.5 m* from the *west* wall (*x=10.5 m*).

Figure 2 shows the location and dimensions of two obstructions were present inside the hall during the experiments and may have influenced the internal air movement. If included in simulation these should be treated as simple rectangular obstructions. The small circles indicate the location of the thermocouples and velocity probes, which are discussed below.

Figures 3, 4 and 5 contain plan, side and end views of the hall respectively, and should further clarify the geometry and dimensions.

Participants should decide for themselves how to incorporate the roof geometry. For a zone model it might be decided to set the (flat) ceiling height such that the volume of the hall is preserved. Participants are free to undertake a series of simulations using alternate strategies, and to comment on the findings.

Material properties

The walls and ceiling consist of a *1 mm* (*0.001 m*) layer of sheet metal on top of a *0.05 m* layer of mineral wool. The floor is constructed from concrete. Table 1 presents the thermal properties of the sheet metal, mineral wool and concrete materials.

Table 1 **Material properties for Part I**

Material		Thermal properties		
		conductivity *($J\ s^{-1}\ m^{-1}\ K^{-1}$)*	density *($kg\ m^{-3}$)*	specific heat *($J\ kg^{-1}\ K^{-1}$)*
metal sheet		54	7850	425
mineral wool		0.2	500	150
concrete		2	2300	900

If included by the participant, the internal obstructions can be modelled as concrete (properties as given in Table 1). However, as the choice of material properties for the internal obstructions is not likely to have an important bearing on the numerical predictions, the obstructions can optionally be treated as adiabatic, i.e. no heat transfer.

All surfaces are assumed to have an emissivity of 0.95, i.e. almost black body, and a convective heat transfer coefficient of $10\ J\ s^{-1}\ m^{-2}\ K^{-1}$.

Ambient conditions

Ambient pressure and temperature are 101300 $N\ m^{-2}$ and 20 $°C$ respectively.

Ventilation conditions

Mechanical exhaust ventilation is operational for one case, with a constant volume flowrate of $11\ m^3 s^{-1}$ drawn through the *1 m* diameter exhaust duct. For this case there are two doorway openings as described above.

For the other two cases the mechanical exhaust system does not operate and the doors are closed. Ventilation is restricted to infiltration through the building envelope. Exact information on air infiltration during these tests is not available. However, following discussions with the scientists involved in the experiments, it is recommended that air infiltration be modelled by including four small, square openings to the outside ambient environment, each opening having an area $0.5\ m^2$. For the purpose of the benchmark exercise it is suggested that two openings be located in the *east* wall, one at floor level and *12 m* above the floor, and two at the opposite end of the hall in the *west* wall. Table 2 shows the co-ordinates of the centre of the four openings.

Note that air infiltration should be ignored in the two cases with mechanical ventilation and doors open.

Table 2 Openings to simulate effect of air infiltration in Part I

Opening (0.707m x 0.707m)	Co-ordinates of centre x (m)	y (m)	z (m)
1	0	6.9	0.354
2	0	6.9	12
3	27	6.9	0.354
4	27	6.9	12

Fire Source

A single fire source was used in each test, its centre located *16 m* from the *west* wall and *7.2 m* from the south wall (*x=16 m, y=7.2 m*) as indicated in Figure 2. For all tests heptane was burned on top of water in a circular, steel tray. The fuel surface was *1 m* above the floor. Two tray diameters were used, *1.17 m* for one case and *1.6 m* for the other two. The trays were placed on load cells, and the mass release rate then calculated from the time derivative of the load cell weight readings.

For the three cases defined below the fuel mass release rate ($\dot{m}_f$) is provided as an input parameter. The choice of combustion mechanism is left to the participant. However, it is suggested that the fuel rate of heat release be modelled as

$$\dot{Q}_f = \chi \dot{m}_f \Delta H_c \qquad (1)$$

Here the heat of combustion (ΔH_c) is taken as $44.6 \times 10^6\ J\ kg^{-1}$. The recommended combustion efficiency (χ) value of *0.8* may be interpreted also as a radiative fraction of *0.2*. For the purpose of the benchmark exercise, it is suggested that as in the first benchmark exercise a value of *12%* be assigned to the lower oxygen limit parameter in those combustion models that make use of it. However, participants are encouraged to investigate other values if they believe this to be important.

Instrumentation

Data was obtained from the instrumentation described below, against which numerical predictions can be compared:

1. Three vertical thermocouple trees, located as shown in Figure 6, on the centre *y*-plane at distances *1.5 m, 6.5 m* and *20.5 m* from the *west* wall. The vertical distribution of thermocouples, the same for all three trees, is shown in Figure 7. Individual thermocouples are labelled as shown in Figure 7, where *T2.5*, for example, refers to the fifth thermocouple on tree number 2. Each thermocouple was a *0.1 mm* K-type. Note that the readings from these thermocouples were used to calculate a layer height and upper layer temperature as described below.

2. Two horizontal thermocouple grids centred directly above the fire source at a height of *7 m* and *13 m*. Both grids consisted of nine *0.5 mm* K-type thermocouples arranged in a 3 by 3 array. However, for the benchmark exercise attention is focussed only at the centre

thermocouple at each height, directly above the centre of the fire tray. These are labelled as *TG.1* and *TG.2* in Figure 7.

3. For the case with mechanical ventilation and open doorways, a vertical column of bi-directional probes to measure gas velocity was located in each doorway opening. Each column contained three probes located on the vertical centre-line of the opening at the heights shown in Figure 7. Note that a positive value indicated flow from the outside to the inside of the hall. The velocity measurements may be used to estimate the net flow of air through the opening.

Two-layer data reduction

A two-layer zone model will predict upper and lower layer properties, and the height of the interface separating the layers. Therefore, to make comparisons between experimental measurements and zone model predictions, the thermocouple data must be reduced in some way.

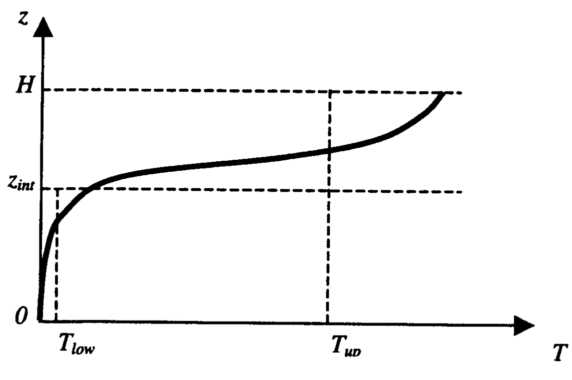
Participants will be provided with the measurement data for all thermocouple locations, and will be free to make their own data reduction to generate upper/lower layer and interface height 'measurements'. However, the method described below will be used as a 'baseline' method and the resultant layer values will be provided along with the 'raw' measurement data.

Furthermore, participants using CFD and network models will be invited to calculate 'upper layer' and 'lower layer' temperatures and an 'interface height' for comparison against zone model predictions. For consistency, the method described below, based on predictions of temperature at the thermocouple tree locations, should be used. If they wish, participants may in addition use their own methods for calculating 'upper layer' and 'lower layer' temperatures and an 'interface height' (and should document these methods).

<u>Layer temperature and interface calculation</u>

The one-dimensional analytical method presented here allows an upper layer temperature (T_{up}), lower layer temperature (T_{low}) and interface height (z_{int}) to be calculated given a discrete set of temperatures (T_i) at heights above floor level (z_i), $i=1,N$.

Consider a continuous function $T(z)$ defining temperature as a function of height z, from 0 (floor level) to H (ceiling).



Then, from the zone model concept and the conservation of mass, we may write

$$(H - z_{\text{int}})T_{up} + z_{\text{int}} T_{low} = \int_0^H T(z)dz = I_1 \tag{2}$$

$$\left(H - z_{\text{int}}\right)\frac{1}{T_{up}} + z_{\text{int}}\frac{1}{T_{low}} = \int_0^H \frac{1}{T(z)}dz = I_2 \tag{3}$$

Algebra then gives

$$z_{\text{int}} = \frac{T_{low}\left(I_1 I_2 - H^2\right)}{I_1 + I_2 T_{low}^2 - 2T_{low}H} \tag{4}$$

Here, T_{low} is taken as the temperature at the lowest discrete measurement location (T_1) and I_1, I_2 are calculated from the discrete data set using a quadrature rule, e.g. Simpsons Rule. T_{up} is then calculated by applying the mean value theorem over the interval $z=z_{int}$ to $z=H$

$$T_{up} = \frac{1}{H - z_{\text{int}}}\int_{z_{\text{int}}}^{H} T(z)dz \tag{5}$$

In reducing the thermocouple tree data it is proposed that the average of the three values (one from each tree) is taken at each distance above the floor.

Exercises

The three cases to be simulated are summarised below. Details of geometry, material properties, ambient conditions, ventilation rates and instrumentation are as defined above. The specifications given here represent the 'baseline' scenarios. Participants are invited to perform study variations on these cases in order to gain insight into the performance of the fire models used. However, the three 'baseline' cases should be given priority, and furthermore *case 1* should be given highest priority.

The fire source should be taken as pure heptane, located as described above. For *case 1* the pool diameter is *1.17 m* while for *cases 2* and *3* it is *1.6 m*. Table 3 defines the fuel mass release rate for each case at discrete times in minutes. A piecewise linear polynomial should be assumed, i.e. interpolate linearly between the given points.

Table 4 summarises the ventilation conditions for the three cases. Natural leakage should be modelled as described above.

Each case should be modelled for the duration of the fire, assuming the fire to have stopped after the last entry in Table 3, i.e. 7.5 minutes of *case 1*, 7 minutes for *case 2* and 6 minutes for *case 3*.

Table 3 **Fuel mass release rates for Part I**

Case 1			*Case 2*			*Case 3*	
t (min)	*dm/dt (kg s^{-1})*		*t (min)*	*dm/dt (kg s^{-1})*		*t (min)*	*dm/dt (kg s^{-1})*
0	0		0	0		0	0
0.22	0.033		0.23	0.057		0.22	0.064
1.5	0.045		0.5	0.067		1.05	0.084
4.8	0.049		1.52	0.081		2.77	0.095
5.45	0.047		3.22	0.086		4.27	0.096
6.82	0.036		4.7	0.083		4.87	0.091
7.3	0		5.67	0.072		5.5	0.07
			6.2	0.06		5.75	0
			6.58	0			

Table 4 **Ventilation conditions for Part I**

Case 1		*Case 2*		*Case 3*
doors closed no mech. exhaust natural leakage		doors closed no mech. exhaust natural leakage		doors open (*0.8 m x 4m*) mech. exhaust (*11 m^3 s^{-1}*) ignore natural leakage

Reporting procedure

The reporting schedule is summarised in the Scheduled Activities above. This section documents the format to be adopted when submitting predictions to BRE in September 2002.

Participants should submit data in either a text file or Excel spreadsheet, and also summarise their findings and modelling assumptions.

The 'raw' prediction data at each reported time will occupy a single record (text file) or row (spreadsheet), with each quantity (e.g. layer height) occupying one field (text file) or column (spreadsheet). While the first field or column should be the time value, the ordering of the remaining fields/columns is left to the participant. However, each field/column should be clearly labelled and the units stated. Numbers may be formatted as deemed appropriate, e.g. fixed number of decimal places, scientific notation (1.5e+2), etc. As a hypothetical example, part of a text file format might appear as below,

Time(s)	T1.1(C)	T1.10(C)	V1.1(m/s)	Layer height(m)
0.	0.	0.	-0.05	19.
10.	0.	0.2	-0.06	19.
30.	0.1	2.8	1.1	16.

It is suggested that results be reported at 10-second intervals. However, this is a guideline only and not a formal requirement (sufficient points to produce representative graphs is the minimum requirement).

Table 5 includes a list of suggested variables to be reported for zone and CFD models (acknowledging that for network models the number of reported variables will be somewhere in between). If a fire model does not output a particular variable, then the participant should ignore it. The number of variables to be reported depends in part on the fire model, with CFD models allowing for a greater number of outputs. Participants are free to include other variables that they consider important.

In addition to the tabulated results, participants are asked to summarise the main modelling assumptions and inputs used. This will include a short summary on the following topics at least (one or two paragraphs on each topic):

- Heat release (combustion) mechanism. This could be a combustion model or a simple heat release source term. Issues such as the lower oxygen limit should be reported.
- Radiation treatment (if included. Important issues may include the treatment radiation transfer to solid surfaces, the absorption/emission in the gas phase and radiation from soot plume.
- The zonal approximations used and main empirical correlations (in the case of a zone model).
- The number of control volumes or elements (in the case of a CFD model), or equivalently the number of network elements (in the case of a network model).
- The turbulence model (in the case of a CFD model).
- Roof geometry assumptions (this relates mainly to zone models).

Table 5 Reported variables for Part I

Zone	CFD
Heat release rate of fire	Temperatures at thermocouple trees (T1.1,...,T1.10,T2.1,...,T2.10,T3.1,...,T3.10)
Interface height	Temperatures at plume thermocouples (TG1.1 & TG.2)
Upper layer temperature	Infiltration flow rate (cases 1 & 2)
Infiltration flow rate (cases 1 & 2)	Mass flow rate in/out door 1 (case 3)
Mass flow rate in/out door 1 (case 3)	Mass flow rate in/out door 2 (case 3)
Mass flow rate in/out door 2 (case 3)	Velocities at the two doorways (case3) (V1.1,...,V1.3,V2.1,...,V2.3)
Total heat loss rate to solid boundaries	Total heat loss rate to solid boundaries
Heat loss through mech. exhaust (case 3)	Heat loss through mech. exhaust (case 3)
Plume temperature	Interface height (using reduction of thermocouple tree data)
	Upper layer temperature (using reduction of thermocouple tree data)
	Total heat release rate (within whole hall)

Part II – Extended NPP Scenarios

Introduction

Part II has been added as an optional extension to the benchmark exercise. It includes three scenario cases inside a rectangular building with dimensions comparable to those of a real turbine hall. The fire size has been chosen to produce temperatures that may be capable of damaging equipment or cables.

As in Part I mechanical exhaust is specified in a sub-set of cases. Targets have been added to Part II to allow the onset of damage to be studied.

Geometry

Figure 8 shows the geometry and dimensions of the building, which are comparable to those of a real turbine hall. For the benchmark exercise there is a doorway opening in the *west* wall and at the opposite location in the *east* wall.

Material properties

To simplify the modelling task, assume the floor, walls and ceiling to be constructed from concrete, with the thermal properties as given in Table 1, and a thickness of *0.15 m*. Again, assume an emissivity of 0.95 and a convective heat transfer coefficient of $10\ J\ s^{-1}\ m^{-2}\ K^{-1}$.

Ambient conditions

As specified for Part I.

Ventilation conditions

Ventilation is provided in all three cases through a doorway opening in the *west* and *east* walls as shown in Figure 8. In two cases both openings have dimensions *1 m* wide by *4 m* high, while for the third case the openings are *4 m* square. Figure 9 shows the location and dimensions of the doorway opening more clearly. The dashed line indicates the location of the larger square doorway in the third case.

In two cases there is mechanical exhaust through 12 vents at ceiling level. Each vent is square with dimension *1 m.* Figure 8 shows the location of the 12 vents.

Fire Source

For all cases, heptane is burned in a square, *4 m* by *4 m*, tray such that the surface of the fuel is *1 m* above the floor. The fire is located centrally inside the hall as indicated in Figure 10. Fuel and combustion properties are as specified for Part I.

The mass release rate of the pool fire ($\dot{m}_f$) grows from zero to a steady value $1.55\ kg\ s^{-1}$ (derived from published data for heptane pool fires [4]) as follows,

$$\dot{m}_f = \alpha t^2 \tag{6}$$

Here t is the time in seconds from the start of the fire, and α is a constant with value $5.325x10^{-6}\ kg\ s^{-3}$. This value is derived from an assumed NFPA ultra fast t-squared growing fire [5]. Equation (6) defines the mass release rate for the first nine minutes, at which time it reaches the steady value $1.55\ kg\ s^{-1}$ which is maintained for the next 11 minutes (giving 20 minutes total duration).

Targets

To make Part II relevant to practical applications three cable targets have been introduced, similarly to the first benchmark exercise. Each cable is a *50 mm* (*0.05 m*) diameter power cable, assumed to consist entirely of PVC. The thermal properties of the cable material are the same as in the first benchmark exercise, repeated below in Table 6.

Table 6 Material properties for cable targets

conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)	density ($kg\ m^{-3}$)	specific heat ($J\ kg^{-1}\ K^{-1}$)	emissivity	convective htc ($J\ s^{-1}\ m^{-2}\ K^{-1}$)
0.092	1710	1040	0.8	10

A structural beam target is included also. To simplify the modelling, this is approximated as a horizontally orientated rectangular slab of steel with cross-sectional dimensions of *0.15 m* wide and *0.006 m* thick. Table 7 provides the material properties to be assumed for the steel 'beam' target, where the conductivity, density and specific heat correspond to steel (0.5% carbon) at 20 *°C* [6]. It is assumed for the purpose of this exercise that property values are temperature independent. A damage temperature of *538 °C* is assumed.

Table 7 Material properties for 'beam' target

conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)	density ($kg\ m^{-3}$)	specific heat ($J\ kg^{-1}\ K^{-1}$)	emissivity	convective htc ($J\ s^{-1}\ m^{-2}\ K^{-1}$)
54	7833	465	0.8	10

Figures 9 and 10 show the locations of the three cable targets and the 'beam' target. The cables extend the full length of the hall (*x* direction), and the 'beam' extends the full width (*y* direction). The centre-lines of the three cables are *1 m* from the south wall, and *9 m, 15 m* and *19 m* above the floor respectively. The 'beam' centre-line is midway across the width of the hall and *0.5 m* below the ceiling.

Internal ceiling

For the exercises described below, an internal ceiling has been added for some cases, effectively dividing the turbine hall into two levels. This makes the geometry more representative of a 'real-life' situation.

It is assumed that the internal ceiling is located *10 m* above ground level and again constructed from *0.15 m* thick concrete (material properties as given in Table 1). Furthermore, there is a hatch opening with dimensions *10 m* by *5 m* within the internal ceiling, providing a connection between the lower and upper levels. Figure 11 shows the location of the internal ceiling and hatch opening.

Exercises

The exercises are divided into two groups of three, where there the first group (cases *1a*, *2a* and *3a*) does not include the internal ceiling (i.e. a single compartment), and the second group (cases *1b*, *2b* and *3b*) includes the internal ceiling (i.e. two compartments) and the hatch opening.

The cases to be simulated are summarised below in Table 8. Note that *case 1b* is the same as *case 1a* but with the addition of the internal ceiling, and likewise for the other cases. Each case lasts for 20 minutes, or until the participant decides there is no need to proceed further, e.g. the cables and 'beam' are damaged.

Case 1 takes highest priority in both the '*a*' and '*b*' groups. While the cases with the internal ceiling are perhaps the more interesting, and arguably warrant priority, it is acknowledged that these are more complex to model and so participants are free to concentrate on the 'simpler' single compartment cases if preferred.

Table 8 Cases for Part II

Case 1a	*Case 2a*
1m x 4m doorway openings no mechanical exhaust ventilation	*1m x 4m* doorway openings *16* $m^3\ s^{-1}$ mechanical exhaust ventilation (divided evenly between the 8 vents)
Case 3a	*Cases* 1b, *2b* and *3b*
4m x 4m doorway openings *80* $m^3\ s^{-1}$ mechanical exhaust ventilation (divided evenly between the 8 vents)	As for *cases 1a*, *2a* and *3a*, but with addition of the internal ceiling partition, dividing the volume into two levels

Reporting procedure

Predictions should be reported in September at the same time as for Part I.

<u>*Cases 1a, 2a* and *3a*</u>

The format and variables for group '*a*' cases (single compartment) are as for Part I, with the following additions or amendments:

- The three vertical thermocouple trees are at the locations shown in Figure 10. These are of relevance to CFD models, where it is requested that gas temperatures be provided at 1-meter intervals in height (labelling the locations *T1.1 – T1.19* etc similarly to that done for Part I).
- As for Part I, the gas temperature directly above the fire is requested at two locations (CFD models), but now at heights *9 m* and *19 m*.
- Three doorway velocities should again be considered at *0.5 m*, *1 m* and *3.5 m* height, on the vertical centre line of each opening.

- The total heat loss through the doorway opening should be provided if possible.
- Upper and lower layer oxygen concentration should be provided in the case of zone models. For CFD models the oxygen concentration at the thermocouple tree locations should be provided.
- For each cable target and the 'beam' target the following should be provided, where possible, at each reported time:

  ⇒ maximum incident flux

  ⇒ maximum surface temperature

  ⇒ maximum centre-line temperature

  Here the maximum refers to the maximum along the length of the cable or 'beam'. If they wish, participants may provide the values at the mid-point (i.e. at $x=40\ m$ for the cables and $y=20m$ for the 'beam') allowing a simpler conduction modelling approach to be used.

Participants should provide comments on the likelihood of damage to the targets, and if so at what time into the fire the damage occurs.

Cases 1b, 2b and 3b

The reporting procedure is as for the group '*a*' cases above, except that the two levels should be accounted for. This means that interface heights and upper layer temperatures should be provided for each level (compartment). Furthermore, the transfer of mass and heat through the hatch opening should be reported.

Where gas temperatures are reported, these should be at the same locations as for the group '*a*' cases (except that there is no temperature at locations *T1.10* and *T2.10* because of the presence of the internal ceiling, and so a blank entry should be provided for this location).

References

1. International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications – Summary of Planning Meeting (24th-25th October 1999, University of Maryland, USA), NUREG/CP-0170, February 2000.

2. International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications – Benchmark Exercise # 1 – cable tray fires of redundant safety trains, 11 September 2000.

3. International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications – Technical Reference Report on Benchmark Exercise # 1, to be published.

4. Babrauskas, V. Estimating large pool fire burning rates. *Fire Technology*, vol. 19, pp. 251-261, 1983.

5. NFPA 204M - Guide for Smoke and Heat Venting. National Fire Protection Association, 1985.

6. SFPE Handbook of Fire Protection Engineering, 2nd Ed., National Fire Protection Association, 1995.

Acknowledgements

The experimental measurements for Part I were collected by VTT as part of the European Coal and Steel Community (ECSC) project *NFSC$_2$*, and are used by permission of the executive committee, SERDEC.

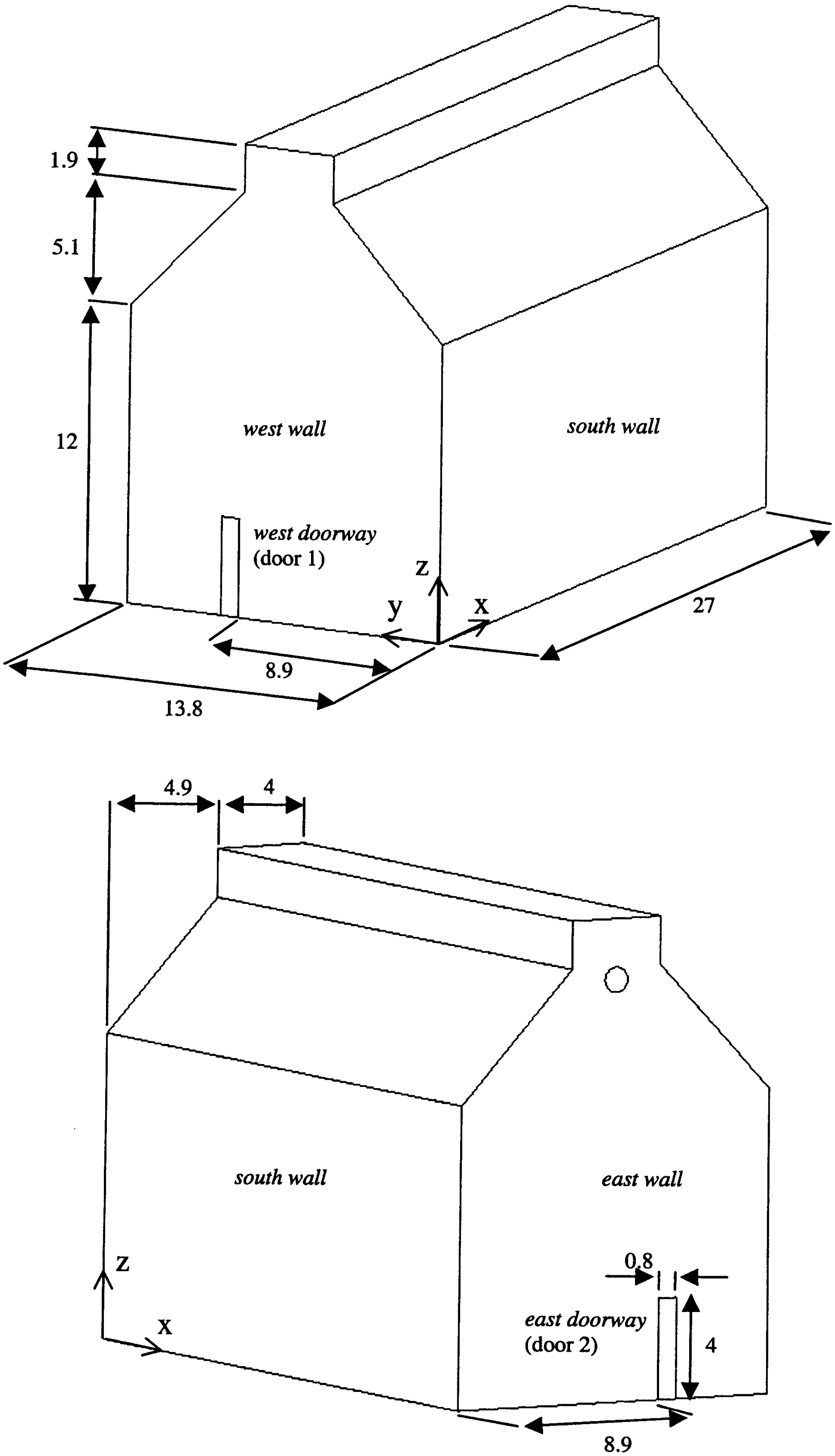


Figure 1 **Hall and doorway dimensions for Part I**

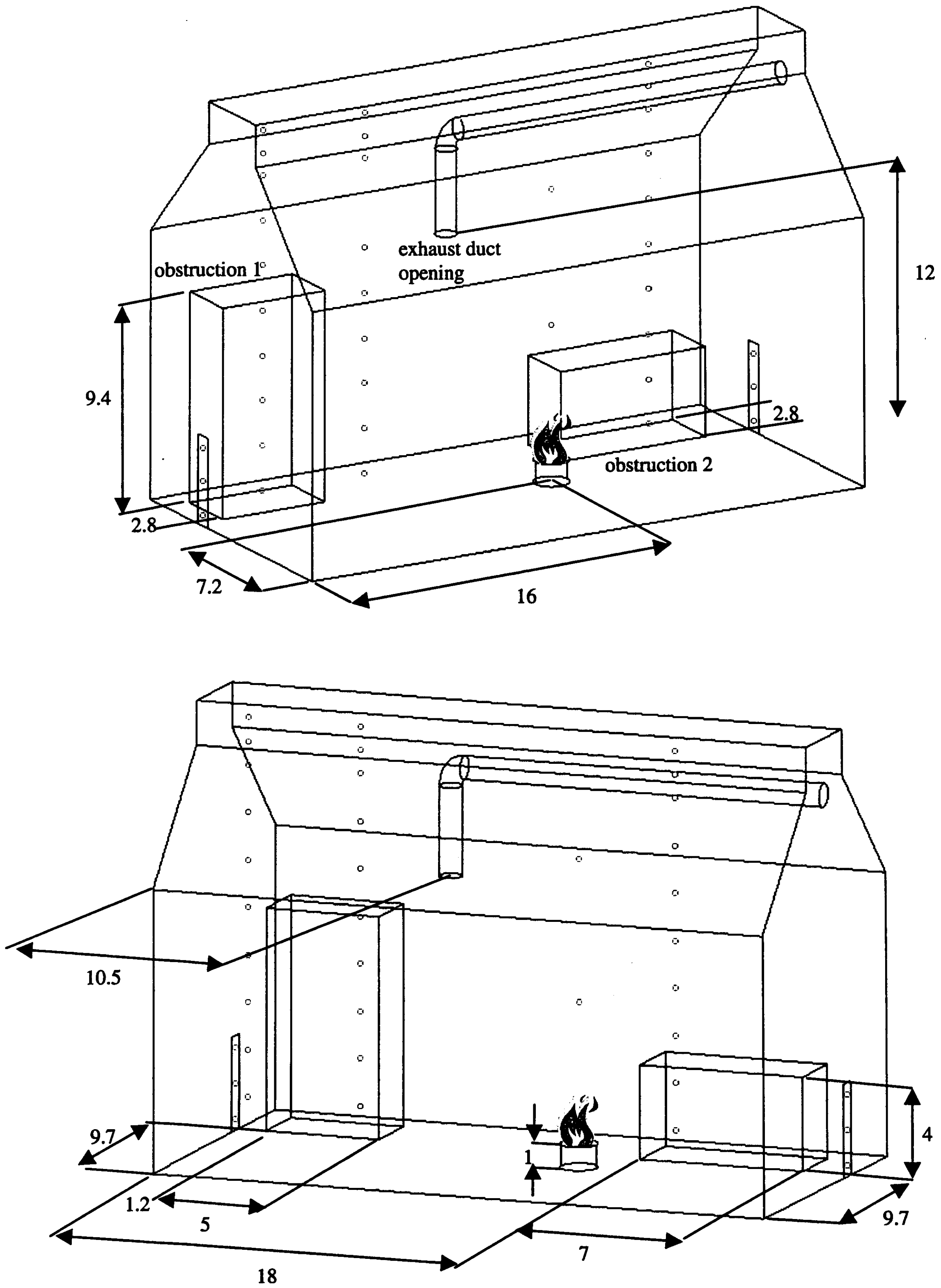


Figure 2 Internal geometry for Part I

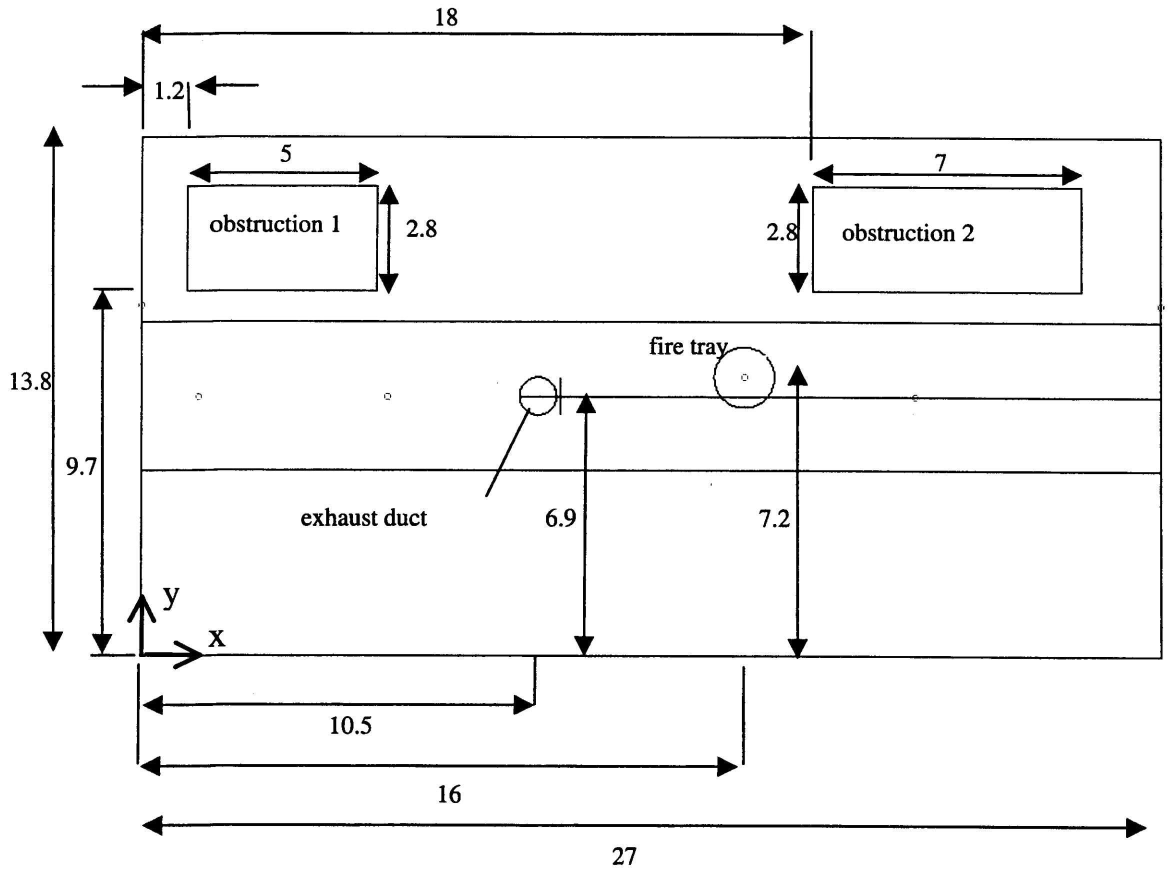


Figure 3 **Plan view for Part I**

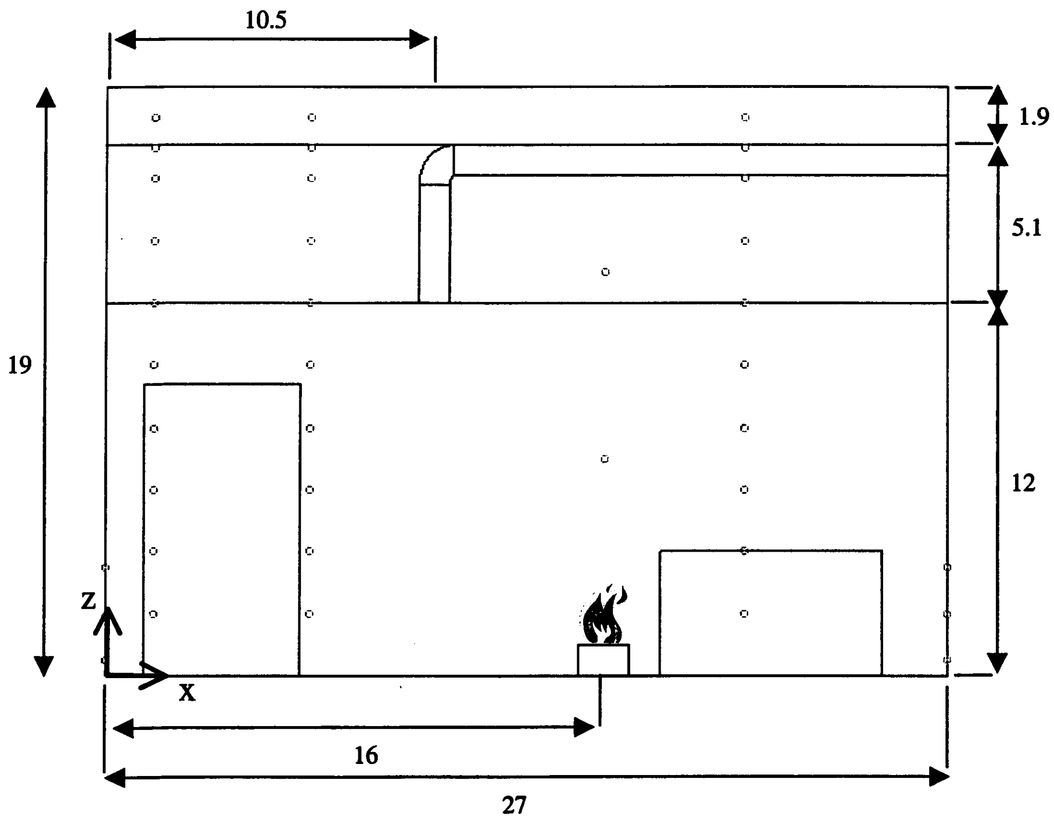


Figure 4 **Side view for Part I**

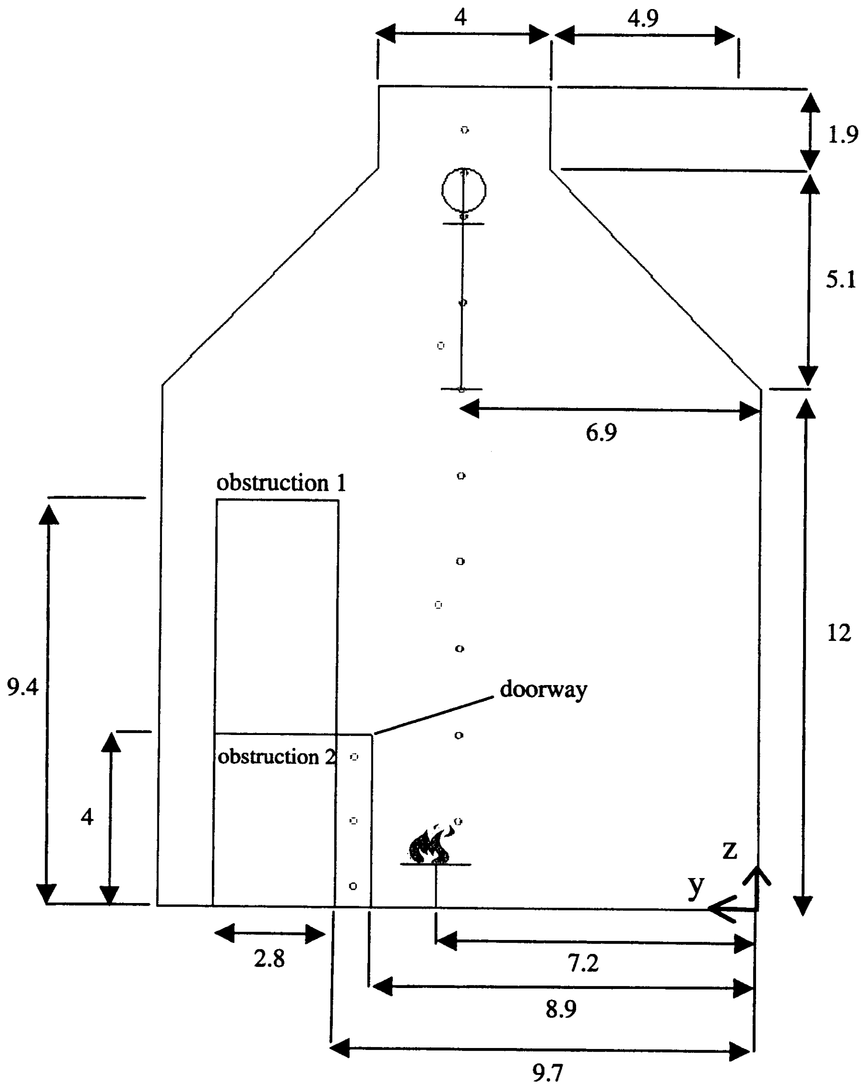


Figure 5 End view for Part I

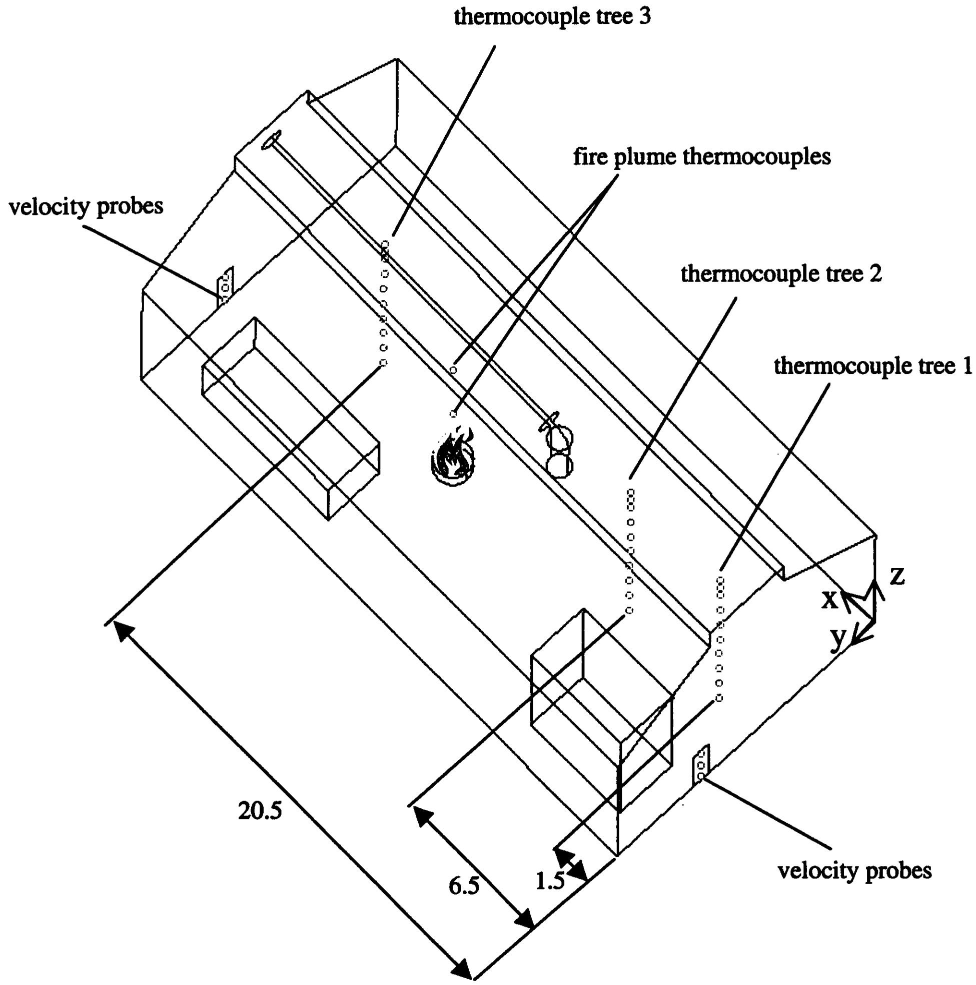


Figure 6 **Experimental Instrumentation for Part I**

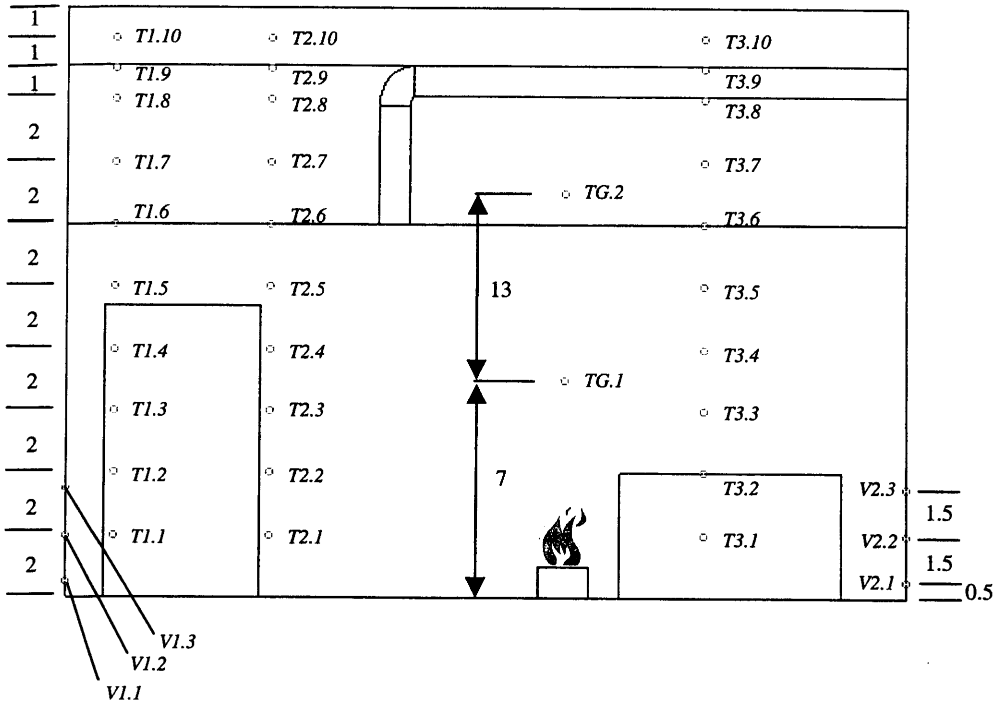


Figure 7 **Individual thermocouples and velocity probes for Part I**

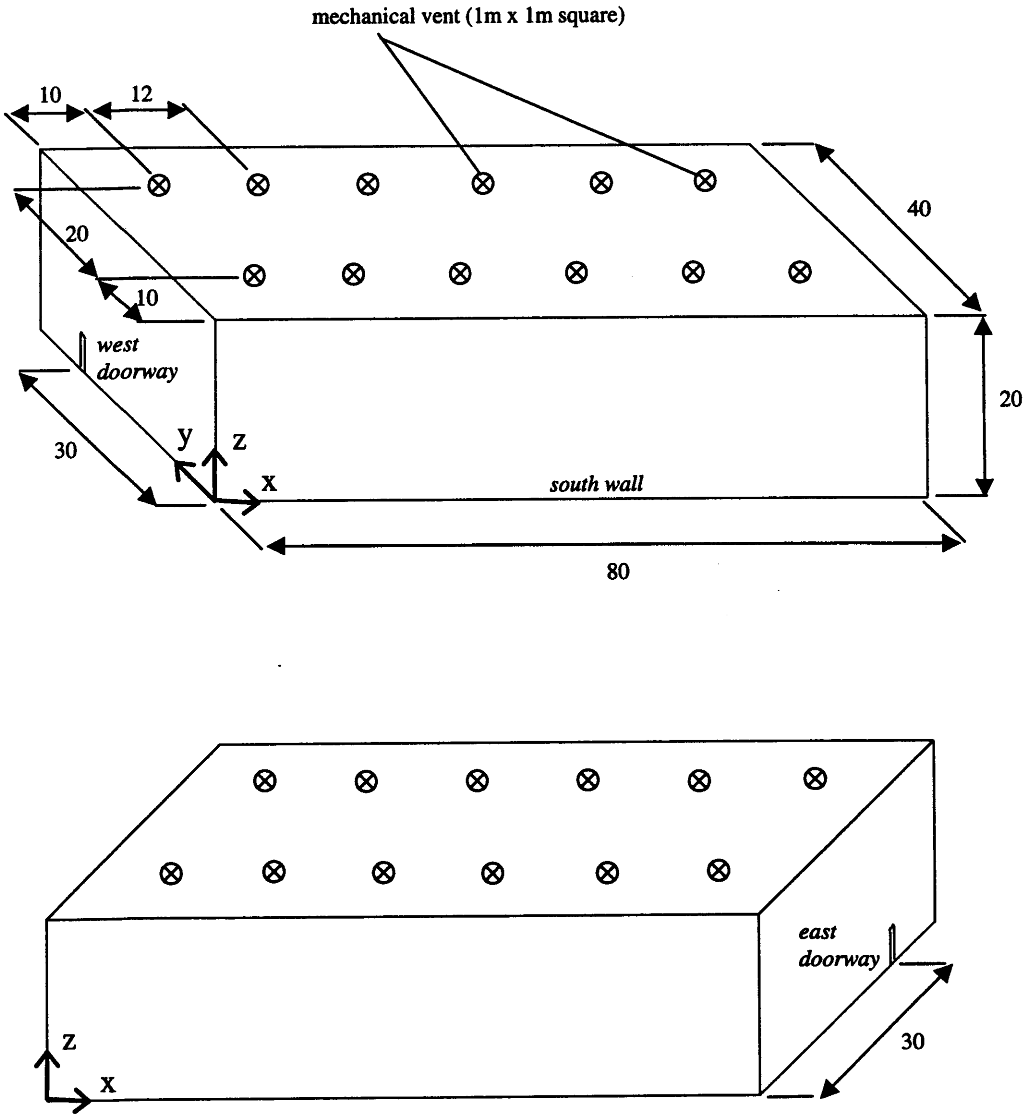


Figure 8 **Geometry for Part II**

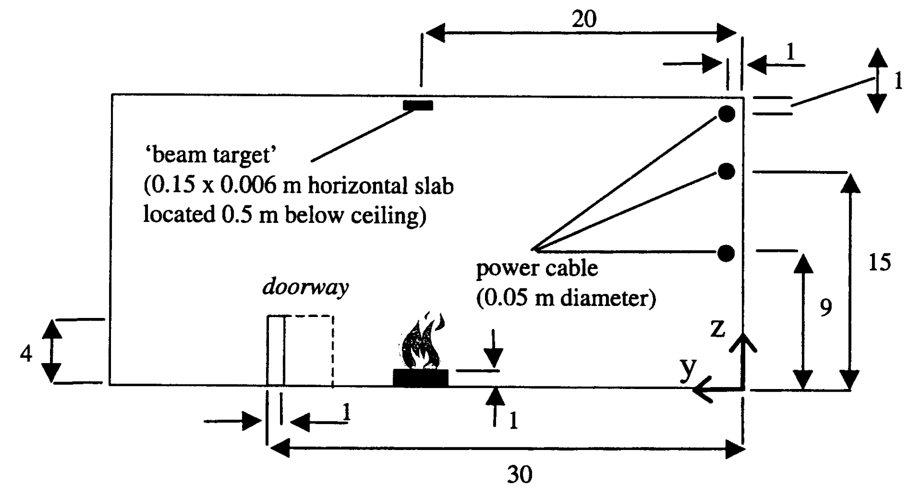


Figure 9 **End view for Part II**

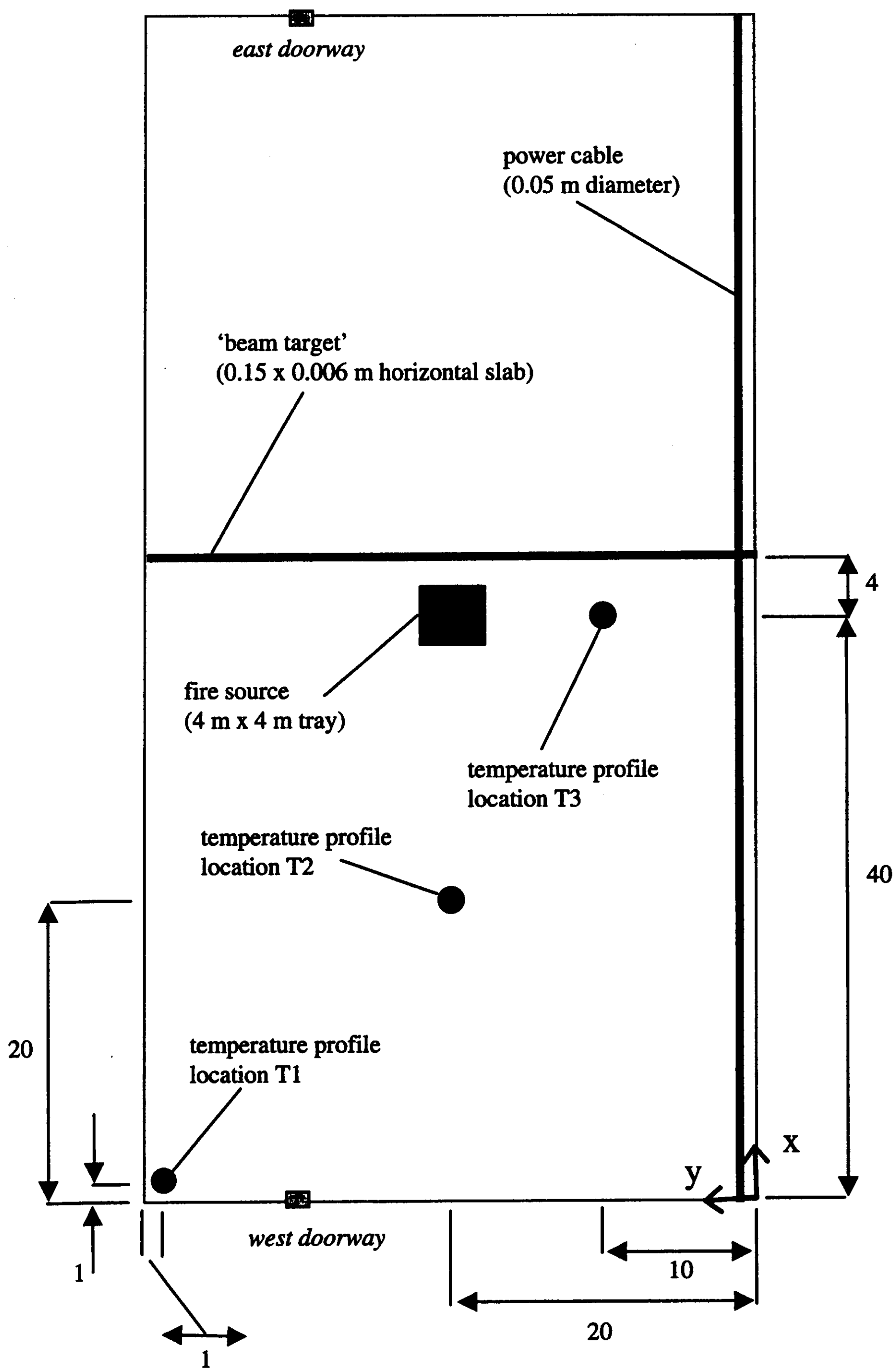


Figure 10 **Plan view for Part II**

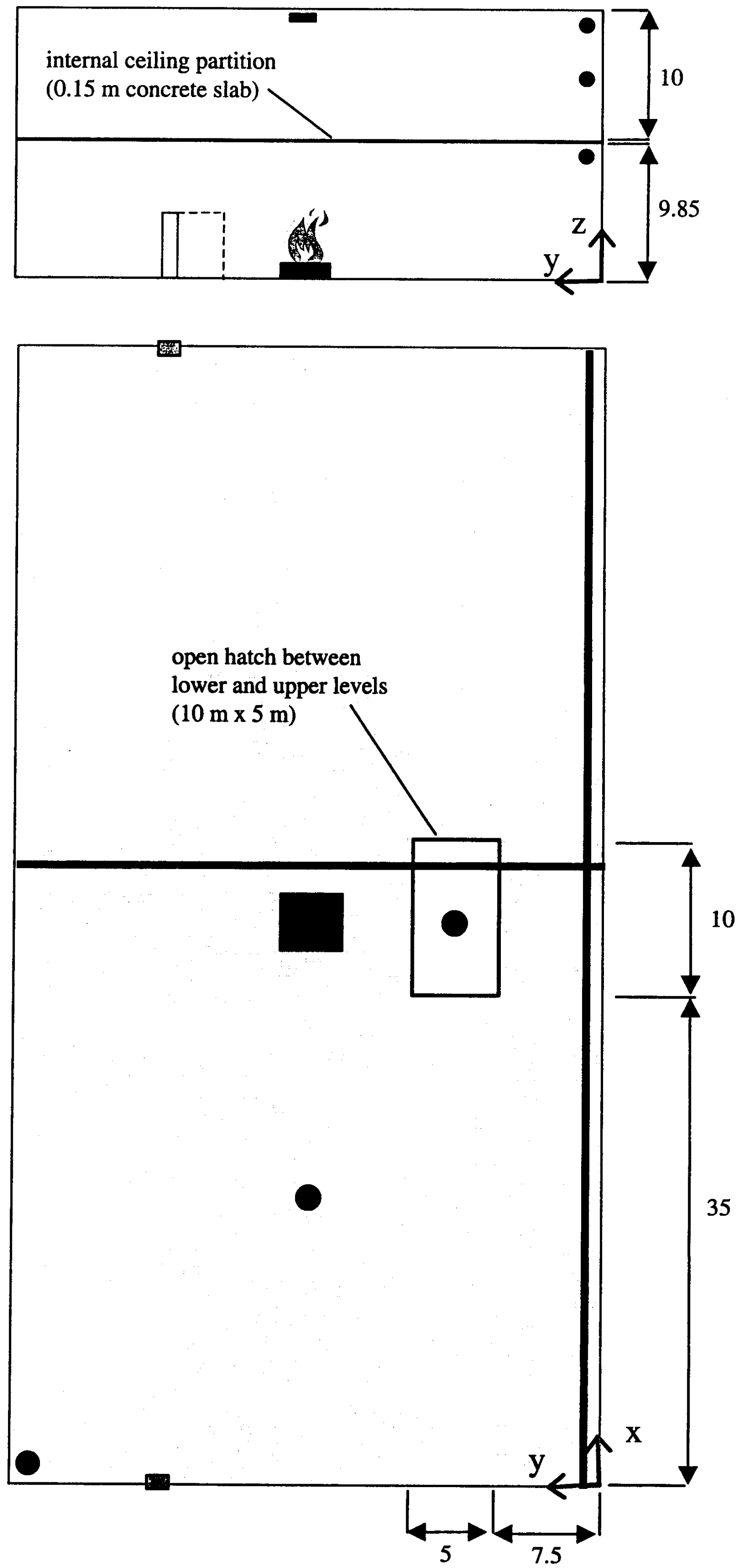


Figure 11 **Internal ceiling partition and hatch for Part II *cases 1b, 2b* and *3b***

Appendix C: Summary Papers

CONTENTS

Appendix D: View Graphs Used for Presentations

Contents